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Ultrashort Pulse Inscription of Photonic Structures in ZnSe and GaAs for Mid Infrared Applications

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14. ABSTRACT

This report results from a contract tasking Heriot-Watt University as follows: B. TECHNICAL PROPOSAL/DESCRIPTION OF WORK:
Military electro-optic sources must be highly reliable in harsh environmental conditions. Waveguide structures provide insensitivity to vibration as well as changes in temperature and pressure. Waveguide devices can also be compact and low cost. Dr K. Schepler at the AFRL Sensors Directorate has great interest in developing robust infrared laser sources using waveguide structures. During a TTCP visit to Herriot-Watt University, we discussed a potential collaboration to develop infrared waveguide structures. This proposal has been developed in consultation with Dr Schepler.
Since the discovery in 1996 that focussed ultrashort pulse laser radiation can modify material refractive index [1], significant research effort has been directed to using ultrashort laser pulses to fabricate integrated optical devices. Waveguides can be fabricated by translating a bulk sample through the focus, effectively writing the optical circuit. This direct-write approach has inherent benefits over conventional fabrication techniques. It does not require expensive clean room facilities, or complex and messy film deposition and etching processes. It also has the capability to fabricate three-dimensional structures, a facility unachievable using conventional techniques. There is also an unprecedented material design freedom with the technique suited to virtually any material transparent to the writing laser. This is a rapid prototyping technique that can allow the development of novel device designs.

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Ultrafast Laser Inscription of Waveguides in ZnSe

FA8655-09-1-3098 - One year report
July 2010

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1.1 Introduction

The aim of this project is to demonstrate ultrafast laser inscription (ULI) of photonic devices in Cr^{2+}:ZnSe with a view to developing the first directly written mid infrared laser source. The development of compact and robust mid infrared sources is of great importance for countermeasures and remote sensing applications. The first stage of the project aims to develop low loss laser inscribed waveguides in polycrystalline ZnSe. Once the optimised fabrication parameters have been determined, waveguides can be written in Cr^{2+}:ZnSe allowing the construction of a compact, mid-infrared waveguide laser.

2.1 Ultrafast Laser Inscription Technique

Ultrafast laser inscription (ULI) is based on the principle of localised material modification by the high peak powers obtained from femtosecond laser sources. The large electric field intensities generated upon focusing femtosecond pulses can be used to induce nonlinear absorption processes inside a focal medium. This process allows optical energy to be deposited in the form a free electron plasma which, in turn, transfers energy to the surrounding material lattice. This transfer of energy can induce localized structural changes which may manifest as a refractive index change. Optical waveguides can be formed by exploiting a positive change in refractive index compared to the bulk material. A major advantage of ULI over standard photolithographic techniques is the ability to create 3 dimensional structures. This is achieved by translating the material through the focus of the fabrication beam, creating the desired structure from the induced positive refractive index change. Precision XYZ stages can be used in conjunction with computer automated control computer aided design (CAD) software to fabricate 3 dimensional optical circuits, Figure 1. This allows a high level of repeatability and a non labour intensive system for fabrication. In addition, ULI offers multiple benefits to the manufacturing process of optical devices. The manufacturing time is very short allowing devices to be written in a matter of minutes. There is no need for clean room facilities and fabrication can be carried out in a maskless environment.

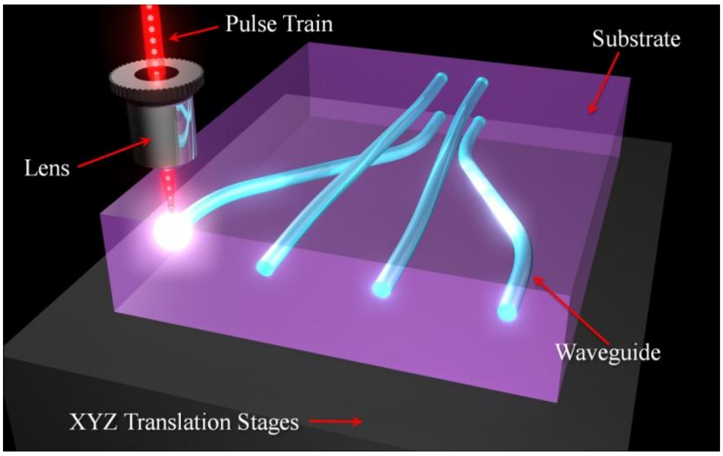

Figure 1. Principle of laser inscription.

The material in which we wish to fabricate waveguides can be translated in two geometries, longitudinal, along the beam axis, or transverse, perpendicular to the beam axis.The longitudinal method limits the sample movement to within the working distance of the lens and so is generally impractical. However, the transverse method creates an asymmetric waveguide cross-section causing difficulties with coupling. This problem can be solved by employing the multiscan technique [1] which allows the desired cross-section of the waveguide to be tailored by overlapping multiple transverse scans, Figure 2. The structure shown in Figure 2 is an example of a type I waveguide where guiding occurs in the modified region created at the focus of the fabrication beam. Type II guiding can be achieved by writing damage lines in the focal medium, inducing stress in the material lattice around the damage, which in turn produces a refractive index change. The end facet cross sections of type I and type II waveguide structures are illustrated below in Figure 2 and 3 respectively.

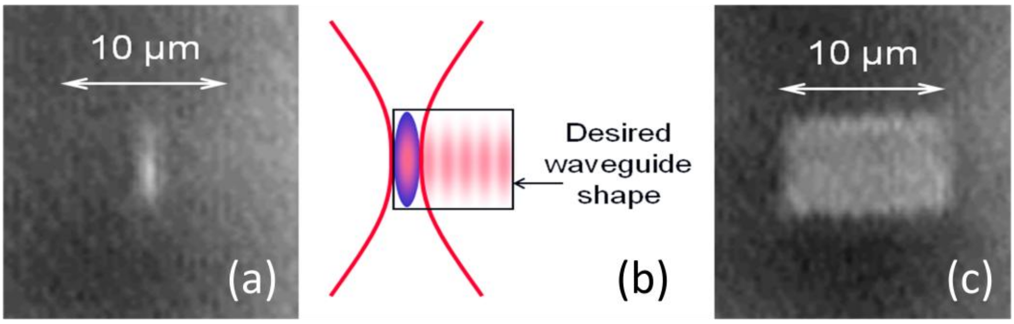

Figure 2. (a) Optical micrograph showing end facet of single scan waveguide. (b) Principle of multiscan technique. (c) Optical micrograph showing end facet of multiscan waveguide structure.

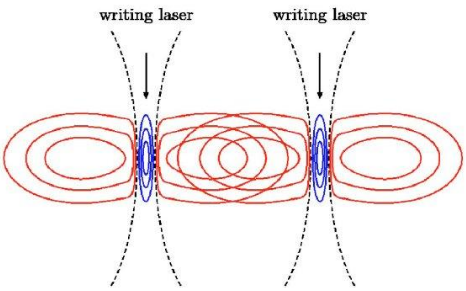

Figure 3. Example of stress fields from two adjacent damage lines written by femtosecond laser. The stress fields overlap to provide a well confined guiding region. [2]

2.2 Ultrafast Laser Inscription in ZnSe

Although ULI has now successfully been used to inscribe waveguides in an incredible range of different materials, its application to highly nonlinear materials has been somewhat limited. One reason for this may be that the high peak powers utilized during ULI can induce nonlinear phenomena, such as self focusing and filamentation, which greatly distort the pulse propagation [3]. Previous attempts of ULI in ZnSe have failed to reach a required threshold for modification [4] despite using high pulse energies of >30 µJ. When we consider that the pulse duration used in this case was 120 fs the peak intensity generated would be over 8000 TW/cm^2. This suggests that unwanted nonlinear effects are responsible for halting the desired index modification processes rather than lack of peak power. It is therefore important to consider the dispersion in the nonlinear refractive index, n_2, of ZnSe, discussed in [5], before attempting ULI. It can be seen that the n_2 value of ZnSe at 800 nm is approximately 100 times greater than silica and 10 times greater than the optical crystal $LiNbO_3$ [6] which has had shown successful fabrication of waveguides using ULI [7]. It can also be seen that the n_2 value of ZnSe is near a local maxima at 800 nm and in fact a fabrication beam with a longer wavelength would be more appropriate.

3 Waveguide Fabrication

3.1 Femtosecond Laser Fabrication

Initial fabrication processes described below were carried out with a Fianium Yb:fibre laser set up in conjunction with Aerotech XYZ stages for translating the samples. The fabrication beam power and polarization were adjusted using the computer controlled apparatus shown below in Figure 4. The two half-wave plates and the quarter wave plate were used in a feedback loop with the control software allowing the output beam to be configured to the desired power and polarization. The laser source provided ~350fs pulses at 1064 nm with a repetition rate of 500kHz and a maximum average power of 360mW. This is equivalent to a maximum pulse energy of 0.72µJ.

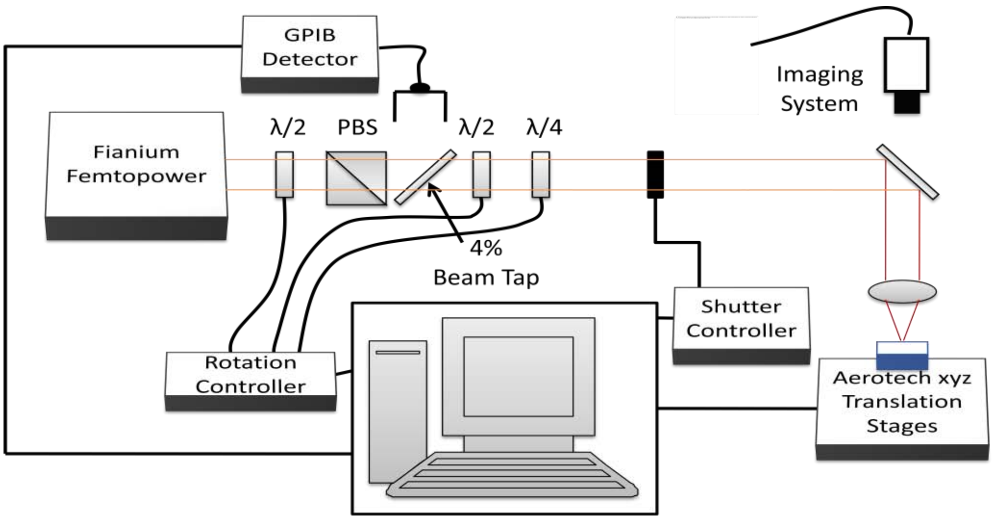

Figure 4. Fianium Laser Fabrication set up.

3.2 Fianium Fabrication Results

The initial fabrication attempts were carried out using the Fianium fibre laser set up described above. The fabrication beam of 0.72 µJ pulses with circular polarization was focused with a 0.6 NA lens, 100 µm below the surface of the materials and multiscan structures were written using 20 overlapping scans separated by 0.4 µm. A range of sample translation velocities from 0.25 – 6 mm.s^{-1} were investigated and the resulting structures were observed under an optical microscope in transmission mode with white light illumination. Figure 5 shows the optical micrograph of the inscribed structures' end facets. It can be seen that only the lower velocities of 1.5mm/s, 1mm/s, 0.5mm/s and 0.25mm/s produced observable changes in the material and that all the structures present highly asymmetric regions of faint modification.

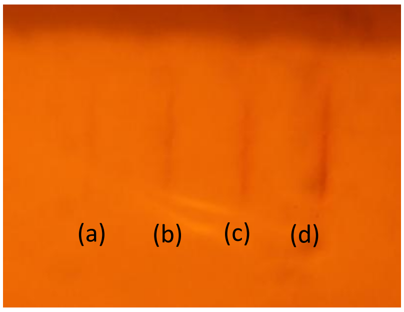

Figure 5. Optical micrograph of sample end facet displaying asymmetric modification of ZnSe with multiscan technique. (a) 1.5 mm.s-1, (b) 1 mm.s-1, (c) 0.5 mm.s-1, (d) 0.25 mm.s-1. The field view is 600 µm x 200 µm.

The same multiscan technique was used to write at 0.1mm/s in an attempt to obtain clearer modification of the material. The structure written at a translation speed of 0.1mm/s , shown in Figure 6, was clearer than previous structures (Figure 5) but only a slight distortion was seen when trying to couple in with a fibre and no guiding was observed as a result of any structure. These results indicate that very little change in the refractive index has been induced.

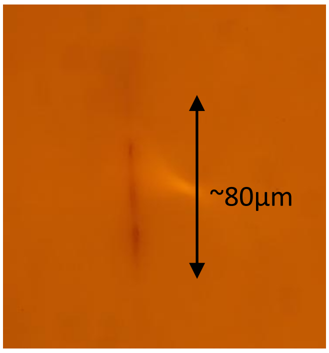

Figure 6. Optical micrograph of structure end facet displaying modification of ZnSe with multiscan technique at a writing speed of 0.1 mm.s-1.

The cross section of the observed structure shown above suggests that the threshold for the three photon absorption process is occurring over a large distance (~80µm) in the z-axis (beam axis) combined with a refocusing cycle responsible for the multiple foci through the structure as indicated in Figure 7. This effect is a direct result of the high nonlinear refractive index, n_2, value of ZnSe and it is clear that longer pulse durations are necessary to overcome this unwanted nonlinear effect.

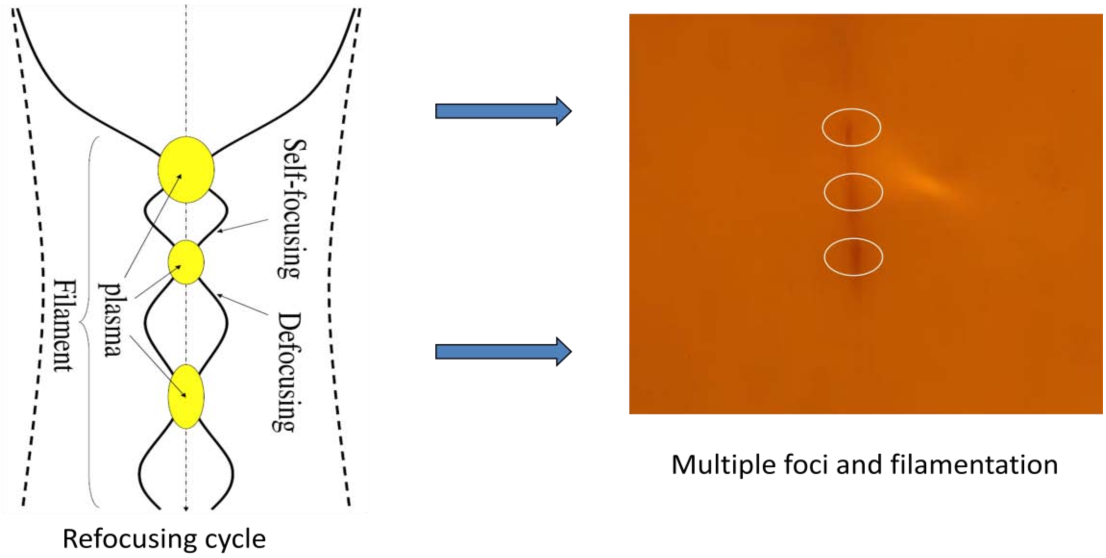

Figure 7. Refocusing cycle causing filamentation and multiple foci. [8]

3.3 Picosecond Laser Fabrication

Longer pulses have been utilized to improve the quality of waveguides fabricated in other nonlinear crystals. The authors of Ref. [7] suggested that the use of longer pulses reduced nonlinear pulse break up and hence enabled sufficient energy to be deposited for the required modification. The use of longer pulses during ULI also increases the role of avalanche ionization [9] in the generation of the free-electron plasma. This enables a more energetic plasma to be induced with lower peak power pulses. The aforementioned multiscan technique can also be useful in overcoming nonlinear effects as it allows a modified area to be built up while using lower peak powers.

Using the new fabrication setup a wider range of parameters could be investigated. The fabrication beam was provided by a commercial Yb-doped master oscillator power amplifier (MOPA) laser system (IMRA µJoule D400). Figure 8 shows the new IMRA fabrication setup with the same power and polarization control arrangement used for the older Fianium system. Importantly, this laser system included an external pulse compressor which allowed adjustment of the pulse duration between ≈350 fs – 2.0 ps. For the work outlined here, pulse repetition rates from 500 kHz to 3 MHz were investigated, the pulse duration was varied between 500 fs to 2.0 ps and a range of pulse energies from 70 – 200 nJ were investigated. The polarization of the laser beam was adjusted to circular and the beam was focused 100 µm below the surface of the sample using an aspheric lens with a numerical aperture (NA) of 0.67. To inscribe the structures, the sample was mounted on high precision air bearing stages (Aerotech) and translated perpendicular to the laser beam propagation direction using translation speeds ranging from 0.25 $mm.s^{-1}$ to 4 $mm.s^{-1}$.

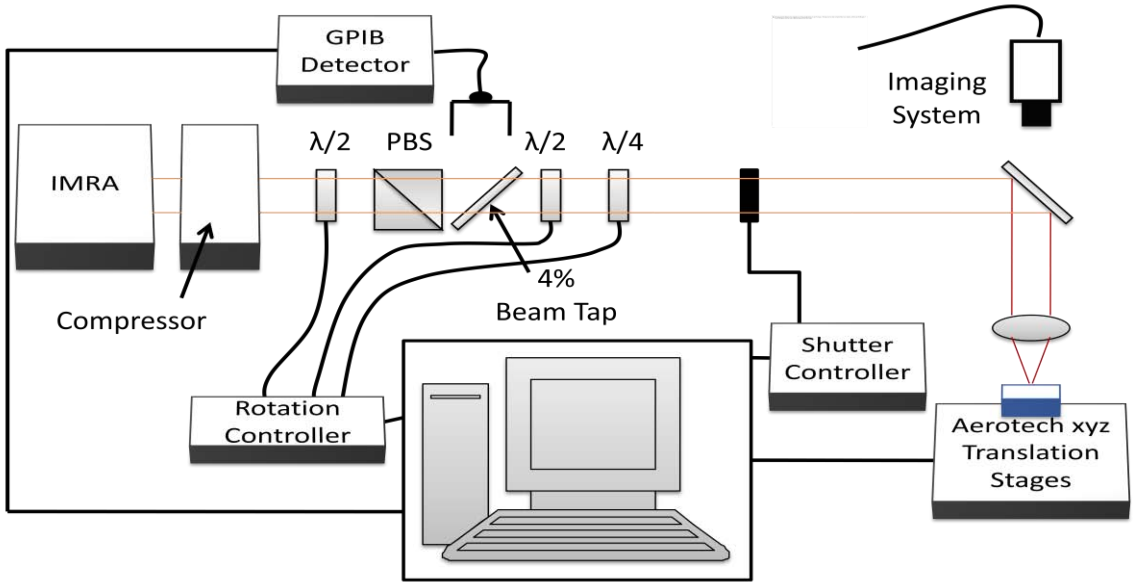

Figure 8. IMRA fabrication laser setup with isolated compressor allowing pulse duration optimization.

Initial characterization of the waveguides was carried out with the bulk optics setup shown below in Figure 9. The 800nm source was a Spectra-Physics Tsunami operated in CW mode. The lens used to couple the light into the waveguide was chosen with a suitable NA to match the waveguide mode field diameter in order to minimize the coupling losses and a photo detector was used to measure the output power with and without the waveguide inserted. This allowed the total insertion loss to be measured which could then be approximated to the sum of the propagation losses and the Fresnel losses.

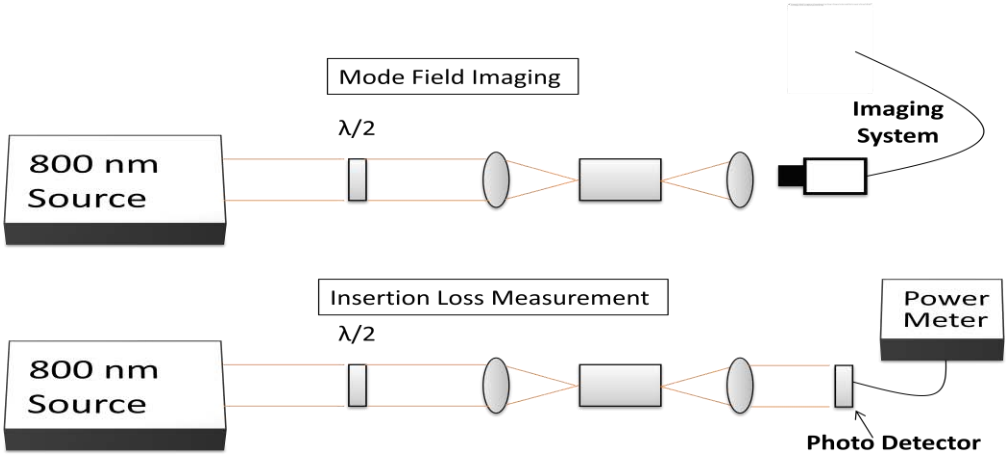

Figure 9. Characterization arrangement.

3.4 Initial IMRA Fabrication Results

Structures were written with the IMRA setup over the range of details described above. Structures inscribed using pulse durations < 1.0 ps exhibited clear material modification, but nonlinear effects were found to result in clear filamentation. In contrast, when the pulse duration was increased to > 1.0 ps, it was observed that self focusing and filamentation could be avoided was observed over a wide range of writing parameters upon increasing the pulse duration to above 1.5 ps. The difference in the structure formed by > 1 ps pulses is shown in Figure 10.

It can be clearly seen that the filamentation has been overcome through use of longer pulses. The structure fabricated using 1.5 ps pulses shows a uniform symmetrical structure and the associated mode field for 800 nm guiding is also shown in Figure 10 to be symmetrical and 10 µm in diameter. This structure was written at a translation velocity of 1 mm.s^{-1} with 85 nJ pulses at a repetition rate of 3 MHz and exhibited a free space total insertion loss of 3.1 dB for a 29 mm waveguide, which was the lowest for all the waveguides at 800 nm. This is comparable to other low insertion loss waveguides and waveguide lasers written in crystals [7, 10].

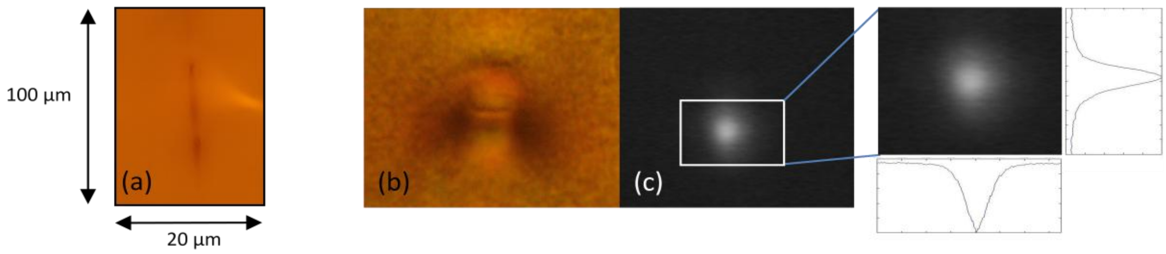

Figure 10. Optical micrograph of (a) structure cross-section fabricated with 350 fs pulse displaying filamentation. (b) waveguide end facet inscribed using 1.5 ps pulses. (c) 800 nm single mode supported by adjacent waveguide. The field view of both (b) and (c) is 30 µm x 30 µm

3.5 1550 nm Waveguides

Guiding for 1550 nm light was investigated with a view to produce guiding at longer wavelengths. This is necessary for future waveguides in Cr^{2+}:ZnSe as the waveguide laser pump source will be approximately 1.9

µm. The requirements for single mode guiding at 1550 nm are substantially different from that of 800 nm and waveguides written with higher pulse energies, > 100 nJ, were found to guide at 1550 nm. Optimisation of the fabrication process was performed by a more in depth investigation of a range of pulse energies, 60-200 nJ, with writing speeds of 0.5, 1, 1.5 mms^{-1}. A limited investigation of pulse widths from 1.5 – 2.5 ps was carried out it in this case as it had been established from our previous work that pulses widths > 1.5 ps achieved the desired material modification. As before, circular polarisation and a 0.67 NA objective were used with the IMRA fabrication arrangement.

Insertion losses were measured using a 1550 nm source in a free space setup similar to the 800 nm characterisation. This was because the waveguides are to be suitable for 1.9 µm pumping and coupling losses from single mode 1550 nm fibre would therefore be irrelevant. Light from the 1550 nm source was coupled into and out of the waveguide using two 10x, NA 0.25 objectives allowing insertion losses to be measured as described in section (3.2.1). Figure 11 shows a waveguide facet image, taken with a microscope in a transmission mode using white light illumination, with its associated mode field.

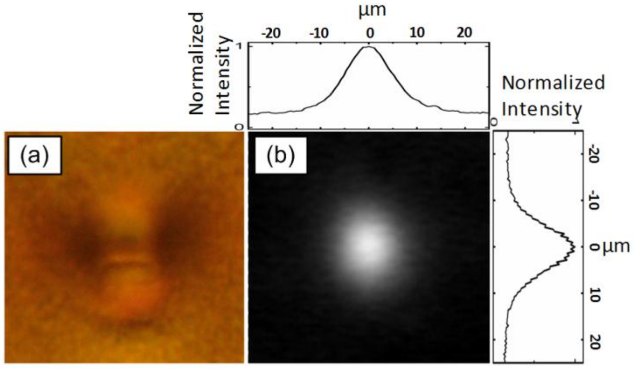

Figure 11. (a) Optical micrograph taken using a microscope in transmission mode with white light illumination showing 1550 nm waveguide facet with (b) associated mode field, near field CCD camera image. The field view of both (a) and (b) is 50 µm x 50 µm.

The insertion loss is taken to be the sum of the coupling, propagation, and Fresnel losses as shown in Equation 1.

$$\alpha_{Insertion} = \alpha_{Coupling} + 2\alpha_{Fresnel} + \alpha_{Propagation} \text{ x } L \qquad \text{Equation 1}$$

where α represents waveguide loss and L is the length of the waveguide. Measuring insertion losses in this way gives an indication of the waveguide quality but does not provide useful information about the origin of the waveguide losses. In order to improve and optimise the waveguide fabrication it is essential to determine the individual values for the coupling, Fresnel and propagation losses. Fresnel losses can be easily calculated by knowing the refractive index of the material but in order to determine the coupling and propagation loss values we need to use another characterisation technique. The high refractive index of ZnSe, 2.5, allows us to use the Fabry-Pérot technique which uses the contrast in an interference fringe pattern to determine the propagation loss of an etalon. This powerful technique allows us to determine separately the propagation and coupling loss contributions.

3.6 Fabry-Pérot Characterisation

The Fabry-Pérot technique [11] was used to determine the propagation losses of the waveguides at 1550 nm. Achieving low waveguide propagation loss is a key objective as the waveguide cross sections can then be easily tailored to the desired dimensions with the multiscan technique to attain low coupling losses.

Light from a tuneable laser source was coupled into and out of the waveguide using two 10x 0.25 NA objectives. The output was then coupled into a near-infrared spectrum analyser which could be used to record the output signal power and wavelength. The tuneable light source was then scanned across 0.2 nm in steps of 3 pm in order to construct the Fabry-Pérot fringe pattern. The linewidth of the tuneable laser source was 700 kHz (5.6 fm) so the fringes could be easily resolved. The contrast between the fringe maxima and minima could then

be used to determine the propagation losses of the waveguide. Figure 12 shows an example of a Fabry-Pérot fringe set.

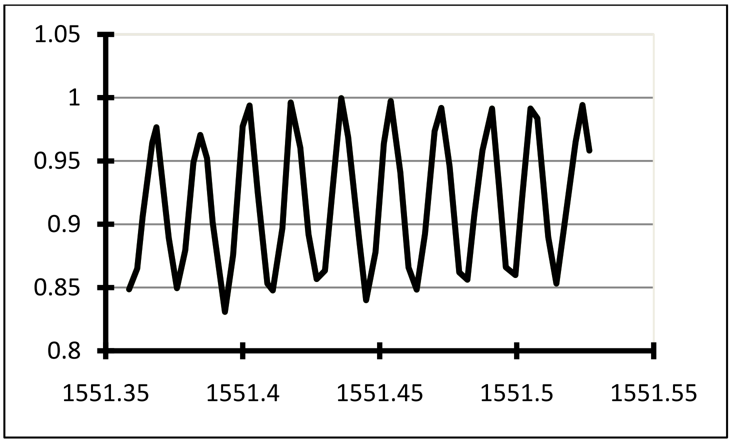

Figure 12. Example of Fabry-Pérot fringe set used for propagation loss calculations.

The contrast of these fringes is defined by Equation 2. This value can then be used to determine the value of the propagation losses as in [11]. Equation 3 shows how this is calculated.

$$K = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad \text{Equation 2}$$

where I_{max} and I_{min} are the maximum and minimum transmitted output respectively and K is defined as the fringe contrast.

$$R\exp(-\alpha L) = \frac{1}{K}(1 - \sqrt{(1 - K^2)}) \quad \text{Equation 3}$$

where α represents the propagation loss per unit length, L, and R is the effective mirror reflectivity which is determined from the Fresnel reflections. It is for this reason that the waveguide facets must be very well polished. Poorly polished facets would result in lower reflectivity and, therefore, error in the loss measurement.

3.6 1550 nm Waveguide Fabrication Results

Repeated Fabry-Pérot fringe measurements were taken over a range wavelengths (1498-1581 nm) and an average propagation loss of 1.1 with standard deviation ± 0.1 dB.cm^{-1} was determined. This is comparable to other directly written waveguides in other crystalline materials [7,10] and marks an important milestone in the development of directly written optical devices in ZnSe. The insertion losses measured were a minimum of 5.0 dB for a 29 mm waveguide. As the insertion loss is composed of the propagation loss, coupling loss and Fresnel loss, we can attribute 1.7 dB to the Fresnel losses and 0.2 ± 0.2 dB to the coupling loss. This value for the coupling loss is in close agreement with the theoretical value, 0.19 dB, calculated from the mismatch of the waveguide mode diameter and the focused beam spot diameter.

4.1 1.9 µm Thulium: Ytterbium Doped Fibre Pump Source

In parallel with the work on waveguide fabrication, a 1.9 µm pump source is being developed with a view to both characterise the waveguides at this wavelength and for pumping the final Cr^{2+}:ZnSe waveguides. The source is based on a Th:Yb microstructured fibre developed at CGCRI Kolkata and can be easily pumped by diode at 980 nm. The current waveguides for 1550 nm light can be for the 1.9 µm pump source by tailoring the waveguide dimensions to match the 1.9 µm mode field diameter using the aforementioned multiscan technique.

5.1 Conclusions and Future Targets

This is the first report of a waveguide directly written into ZnSe using ultrafast laser inscription (ULI) and is a major milestone in the project. Furthermore, the characterisation of these waveguides was carried out over the course of 8 weeks suggesting that the structures are permanent at room temperature. This work has demonstrated that ULI is a practical method for fabricating waveguides in ZnSe paving the way for the development of ZnSe photonic devices for use in the mid infrared. Fine tuning of the inscription parameters could yield even better waveguide performance and further characterisation for 1.9 μm light will be necessary in preparation for Cr^{2+}:ZnSe waveguides. The Th:Yb fibre laser source will fit well with this task. Further investigation into optimisation of the multiscan parameters is currently being conducted in order to achieve waveguides for the mid-infrared. This will allow work to begin on directly written waveguide lasers in Cr^{2+}:ZnSe. This will allow a cavity to be designed to produce the first directly written mid-infrared laser source.

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